METHOD FOR MEASURING THE ABSORPTION COEFFICIENT
AND THE REDUCED SCATTERING COEFFICIENT
OF A MULTIPLE SCATTERING MEDIUM

BACKGROUND OF THE INVENTION

5   ### 1. Field of the Invention

The invention relates to a method for measuring the absorption coefficient and the reduced scattering coefficient of a medium, more particularly to a method for measuring in real time the absorption coefficient

10   and reduced scattering coefficient of a multiple scattering medium.

2. Description of the Related Art

Human tissue is a highly scattering medium, and has the characteristics of having a scattering coefficient

15   much greater than the absorption coefficient thereof. A conventional method of obtaining an image in a scattering medium involves measuring of absorption coefficients so as to obtain an image with contrast. However, when it is desired to obtain the image of an

20   object in a multiple scattering medium, since the light waves are highly scattered, the resultant image is blurred, and the resolution of the image is also reduced considerably. Therefore, if the scattering effect of light in a relatively high scattering medium can be

25   reduced, or if only slightly scattered snake photons and ballistic photons are selected, together with enhancement of the sensitivity to absorption

coefficients, the resolution of an image in the medium can be enhanced. However, this is not suitable for imaging objects in multiple scattering media.

At present, methods for imaging in a multiple scattering medium mainly include time-domain and frequency-domain imaging techniques. The concept of diffused photon density wave (DPDW) is proposed in the frequency-domain technique. DPDW satisfies the diffusion equation, and can be relied upon to obtain definite amounts of the absorption and scattering coefficients of the test object, thereby permitting recovery of the image of an object in the scattering medium. The frequency-domain technique is currently more suitable for imaging in a multiple scattering medium, but has the drawback that the spatial resolution is not high. Thus, how to enhance imaging resolution in applications that involve a multiple scattering medium is currently an important topic in the industry.

SUMMARY OF THE INVENTION

A two-frequency polarized laser, e.g., a Zeeman He-Ne laser, can produce a two-frequency mutually correlated and mutually orthogonal linear polarized photon pair (PPP) laser beam for propagation through a highly concentrated scattering medium to produce a diffused polarized photon pair density wave (DPPDW). Particularly, by means of a polarizer, the mutually correlated and mutually orthogonal linear polarized

photon pair can be effectively converted into a mutually correlated and mutually parallel polarized photon pair. The present invention primarily contemplates the propagation of a mutually correlated and mutually

5 parallel two-frequency polarized photon pair in a multiple scattering medium to form a diffused polarized photon pair density wave while satisfying the diffusion equation. The same result can be achieved if a two-frequency circular polarized photon pair is

10 converted into a mutually parallel polarized photon pair by the use of a polarizer. By measuring directly the amplitude and phase of the DPPDW, the absorption coefficient μ_a and the reduced scattering coefficient

μ_s' of the multiple scattering medium can be measured

15 in real time, in which $\mu_s' = \mu_s(1-g)$, where μ_s is the scattering coefficient, and g is the scattering anisotropic parameter of the multiple scattering medium. The three-dimensional (3-D) distributions of μ_s' and

μ_a are obtained by finding the solution to the diffusion

20 equation so as to obtain optical characteristics of and images in the multiple scattering medium. Further, as oxyhemoglobin (HbO_2) and deoxyhemoglobin (Hb) have different absorption coefficients with respect to the same wavelength, by using a two-frequency laser source

25 (preferably, two two-frequency lasers) having

different center wavelengths, the hemoglobin saturation (S_aO_2) in blood can be measured in real time, and images of hemoglobin saturation distribution can also be obtained.

5   This invention provides a method using a two-frequency, two-polarization laser beam for propagation in a highly concentrated scattering medium so as to form DPPDW. Through optical heterodyne interference techniques and coherence of the polarized

10   photon pair, the magnitude of the phase and amplitude of the DPPDW can be obtained from the heterodyne interference signals, and the absorption coefficient μ_a and the reduced scattering coefficient μ_s' of the scattering medium can be calculated from the phase delay

15   and amplitude attenuation that change with the distance between a laser source and a photo detector.

The object of this invention is to provide a method for measuring the absorption coefficient and the reduced scattering coefficient of a multiple scattering medium,

20   in which, due to coherence of a polarized photon pair, and processing with the use of a heterodyne polarized interferometer, scattering of a light beam by the medium can be reduced, thereby enhancing resolution.

Another object of this invention is to provide a

25   spatial imaging method, in which, by changing measuring positions and recording the measurement results at each of the measuring positions, a complete image of the

multiple scattering medium can be constructed.

According to the present invention, the method for measuring the absorption coefficient and the reduced scattering coefficient of a multiple scattering medium includes: outputting a coherent light beam, the coherent beam including linear polarized P and S wave components having mutually orthogonal polarizations and frequencies ω_P and ω_S, respectively; splitting the coherent light beam into a signal beam and a reference beam, the signal beam and the reference beam including the P wave and S wave components, respectively; projecting the signal beam into the multiple scattering medium; detecting and converting an optical interference signal of the reference beam and an optical interference signal of the signal beam that penetrates the multiple scattering medium and a polarizer, respectively, into heterodyne interference electrical signals; comparing the two heterodyne interference electrical signals to obtain amplitude attenuation and phase delay of the signal beam that penetrated the multiple scattering medium; and inferring the reduced scattering coefficient and the absorption coefficient of the multiple scattering medium at a position where the multiple scattering medium is penetrated with reference to the amplitude attenuation and phase delay thus obtained.

BRIEF DESCRIPTION OF THE DRAWINGS

Other features and advantages of the present invention will become apparent in the following detailed description of the preferred embodiment with reference to the accompanying drawings, of which:

5   Figure 1 is a block diagram showing the construction of an apparatus for implementing a preferred embodiment of a method according to the invention;

Figure 2 is a schematic view illustrating the principle of generating a photon pair with parallel

10   polarization directions in the apparatus of Figure 1;

Figure 3 is a schematic view of an imaging device employed in the preferred embodiment;

Figure 4 is a block diagram of another apparatus for implementing the preferred embodiment;

15   Figure 5 illustrates how P wave and S wave components are adjusted using a $\frac{\lambda}{2}$ wave plate in the apparatus of Figure 4; and

Figures 6A and 6B respectively illustrate the variation in amplitude attenuation and phase delay of

20   DPPDW obtained in an experiment conducted by the applicant.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to Figure 1, a two-frequency, two-polarization laser 100, such as a Zeeman laser,

25   outputs a coherent light beam, which includes mutually correlated and mutually orthogonal linear polarized

waves that include a P wave and an S wave, the temporal frequencies of which being ω_p and ω_s, respectively. The coherent light beam is passed through a polarizer 200 having an azimuth angle θ with respect to an axis (X).

5   As shown in Figure 2, since the angle of polarization direction of the polarizer 200 relative to the P wave is θ, the component of the P wave projected in the polarization direction is $L_p = A_p \cos\theta \exp(i\omega_p t)$, whereas the projected component of the S wave is $L_s = A_s \sin\theta \exp(i\omega_s t)$,

10   thereby generating a photon pair (L_p, L_s) with mutually parallel polarization directions, wherein A_p and A_s are the amplitudes of the P wave and S wave components, respectively.   Thus,   a   two-frequency   mutually correlated and mutually parallel linear polarized

15   photon pair beam is generated accordingly.

A beam splitter 210 splits the linear polarized photon pair beam into a signal beam I_s and a reference beam I_r. The signal beam I_s is focused via a microscopic object lens 220 for optic-fiber input into a signal optical

20   fiber 230. At the same time, the reference beam I_r is sent via a reflecting mirror 240 into a photo detector 250 to generate heterodyne interference reference signals, which can be expressed as follows:

$$I_r(\Delta\omega t) = DC + \Gamma\cos(\Delta\omega t) \text{-------------------} (1)$$

25   in which Γ is the magnitude of the amplitude of the

heterodyne interference signal of the P wave component
and the S wave component in the reference beam I_r.

On the other hand, the signal beam I_s is outputted
from the other end of the signal optical fiber 230, and
5   diffuses into a multiple scattering medium 260 to form
DPPDW. A detector fiber 270 similar to the signal
optical fiber 230 is disposed in parallel at a separation
distance (r) from the signal optical fiber 230 for
detecting the DPPDW. In a photomultiplier tube (PMT) 280,
10   the heterodyne interference signals are generated,
which are outputted through a signal amplifier 290 and
a band-pass filter 300 to an electrical signal processor
310 (e.g., a phase-lock amplifier) for amplitude and
phase measurements.

15   During the aforesaid process, when the polarized
photon pair with mutually parallel polarization
directions of the signal beam I_s enter into the multiple
scattering medium 260, although the coherence and the
degree of polarization (DOP) of most of the polarized
20   photon pairs are decorrelated due to a series of collision
events, during the process of detecting the optical
interference signals, some of the polarized photon pairs
can still maintain their correlation such that a
meaningful heterodyne interference signal is generated,
25   the main frequency of the interference electrical signal
being $\Delta\omega = \omega_p - \omega_s$. Therefore, after filtering through
the band-pass filter 300 having a center frequency of

$\Delta \omega = \omega_p - \omega_s$, other irrelevant noise signals can be clearly removed.

Since only those of the polarized photon pairs which undergo relatively less collision events during passage through the multiple scattering medium can preserve relatively more polarization characteristics and directionality (or spatial coherence) for generating the heterodyne interference signals, the heterodyne interference technique according to this invention can be employed to screen diffused polarized photon pairs with a relatively low degree of scattering to form DPPDW. At the same time, they can also satisfy the diffusion equation. When the photon pairs with mutually parallel polarization directions are projected into a highly concentrated multiple scattering medium 260 and subsequently undergo photo detection, the intensity of the heterodyne interference signals thus generated can be expressed as follows:

$$I_s(\Delta \omega\, t) = DC + \gamma \cos(\Delta \omega\, t + \Delta \Phi) \text{------------------} (2)$$

in which $\Delta \omega = \omega_p - \omega_s$ is the beat frequency of the heterodyne interference signal; γ is the amplitude of DPPDW; and $\Delta \Phi$ is the phase delay. μ_s' and μ_a of the multiple scattering medium can be obtained from the phase delay and amplitude attenuation of DPPDW. Equation (2) can be further rewritten as:

$$I_s(\Delta\omega\, t) = \varphi_0^2 \frac{e^{-k_{2r}r}}{r} \mathrm{Re}\{e^{i(\Delta\omega t + \Delta\phi)}\} \ \text{---------------------} (3)$$

in which φ_0^2 is the rate of energy fluence of DPPDW;

k_{2r} is the real number portion of the wave number k_2 of

DPPDW, $k_2 = k_{2r} + ik_{2i}$; $i = \sqrt{-1}$; and k_{2r} corresponds to the

absorption and scattering characteristics of the signal

beam in the multiple scattering medium.

$$k_{2r} = [3\mu_a(\mu_s' + \mu_a)]^{\frac{1}{2}} \ \text{------------------------} (4)$$

From Equation(3), different separation distances

r_0 and r can be obtained, and $\Delta r = r - r_0$. The amplitude

attenuation of the signal beam in the multiple scattering

medium is:

$$\ln\left(\frac{I}{I_0}\right) = \left[\ln\left(\frac{r_0}{r}\right) - k_{2r}\Delta r\right] \ \text{----------------------} (5)$$

in which (I_0, I) are the intensities of the heterodyne

interference signals at (r_0, r), respectively. Similarly,

$\Delta\Phi$ is the phase delay and can be expressed as follows:

$$\Delta\phi = \frac{n\Delta\omega}{c}\left(\frac{3\mu_s'}{4\mu_a}\right)^{\frac{1}{2}} \cdot r = k_{2i}r \ \text{---------------------} (6)$$

$$k_{2i} = \frac{n\Delta\omega}{c}\left(\frac{3\mu_s'}{4\mu_a}\right)^{\frac{1}{2}} \ \text{--------------------------} (7)$$

in which k_{2i} is the imaginary part of the wave number

k_2 of DPPDW, which corresponds to the scattering and

absorption characteristics of the multiple scattering medium. (μ'_s, μ_a) are, respectively, the reduced scattering coefficient and the absorption coefficient of DPPDW in the multiple scattering medium. n is the refraction index of the medium, and c is the speed of light. From Equations (4) and (7), the following equations are obtained:

$$\mu'_s = \frac{2ck_{2r}k_{2i}}{3n(\Delta\omega)} \text{------------------------------------} (8)$$

$$\mu_a = \frac{n\Delta\omega}{2c}\left(\frac{k_{2r}}{k_{2i}}\right) \text{-------------------------------} (9)$$

Therefore, the characteristics (μ'_s, μ_a) of the multiple scattering medium can be obtained from the amplitude attenuation and the phase delay of the heterodyne interference signals measured by the apparatus shown in Figure 1.

As shown in Figure 3, a two-frequency laser source 400 and a detector 500 are displaced together relative to a multiple scattering medium 600 to perform two-dimensional (2-D) and three-dimensional (3-D) scanning. The spatial distribution of μ'_s and μ_a is obtained from the amplitude and phase data of DPPDW. Then, the diffusion equation is used to recover the object into an image. Details as to image recovery using the diffusion equation can be found in various literature, such as S. Fantini et al., " Assessment of the size,

position, and optical properties of breast tumors in vivo by noninvasive optical methods," *Appl. Opt.* 37, 1982-1989 (1998); and E.L. Heffer et al., "Quantitative oximetry of breast tumors: a near-infrared method that

5   identifies two optimal wavelengths for each tumor," *Appl. Opt.* 41, 3827-3839 (2002). The number of light sources and photo detectors can be adjusted suitably to obtain optimum imaging effects.

        Certainly, as apparent to those skilled to the art,

10   the two-frequency coherent light source can be achieved using various constructions. For instance, a linear polarized single-frequency stabilized laser is used to emit a polarized beam, and the polarization angle thereof is adjusted through a polarization angle

15   adjusting device, such as a $\lambda/2$ wave plate. A polarized beam splitter splits the laser beam into orthogonal polarization directions, and both polarization laser beams are frequency shifted by passing through different frequency adjusting devices, such as acousto-optic

20   modulators (AOM). Hence, the frequencies of the two beams with mutually orthogonal polarization directions can have a discernible minor frequency difference $\Delta\omega$. Then, the beams are integrated once again to become a two-frequency coherent beam that includes the P wave

25   and the S wave. The frequency adjusting device may be an electro-optic modulator or any other similar device.

Alternatively, by enabling a two-frequency laser with two different center wavelengths to undergo light synthesis, the polarized photon pair beam can also be projected into the multiple scattering medium by employing the aforesaid optical system so as to achieve a polarized photon pair for near-infrared spectroscopy (NIRS).

As shown in Figure 4, in another apparatus for implementing the method of this invention, rotation of the azimuth angle through a $\frac{\lambda}{2}$ wave plate 110 can be used to adjust the azimuth angles of the P wave and S wave components of the two-frequency laser beam 100 and the X-Y coordinates so as to form an angle Θ (see Figure 5). After splitting by a beam splitter 190, the signal beam I_s is projected into the multiple scattering medium to be measured. Subsequently, during the process of detecting the optical interference signal of the signal beam I_s, the signal beam I_s is split once again by a polarized beam splitter 130 according to the polarization direction, and the mutually orthogonal linear polarized photon pair are respectively detected by photo detectors 140, 150 and signal processors 160, 170, for conversion into heterodyne interference electrical signals, which can be expressed as follows:

$$I_x(\Delta\omega t) = DC + \gamma\cos(\Delta\omega t + \Delta\Phi) \text{-----------------} (10)$$

$$I_y(\Delta\omega\,t) = DC - \gamma\cos(\Delta\omega\,t + \Delta\Phi) \text{-----------------} (11)$$

By inputting synchronously the two heterodyne interference electrical signals obtained from conversion of the signal beam I_s that penetrated the multiple scattering medium to be measured into a differential amplifier 180, and by subtracting the two signals and amplifying the result for output, a balanced detector can be formed:

$$\Delta I = I_x - I_y = 2\gamma\cos(\Delta\omega\,t + \Delta\Phi) \text{------------------} (12)$$

The output of the differential amplifier 180 is fed to a signal processor 330. At the same time, the reference beam I_r is received by a polarizer 195 and a photo detector 320 from the beam splitter 190, and is subsequently inputted into the signal processor 330 so as to obtain amplitude attenuation and phase delay of the heterodyne interference signals and to enhance the detection sensitivity and signal-to-noise ratio.

Further, as the absorption coefficients μ_a of hemoglobin in the blood in an oxygenated state (HbO_2) and a deoxygenated state (Hb) are obviously different with respect to near infrared wavelengths (λ_1, λ_2) (e.g., $\lambda_1 = 780nm$, $\lambda_2 = 850nm$) (see S. Fantini et al., supra), changes in the hemoglobin saturation (SaO_2) (see E.L. Heffer et al., supra) in the blood can be obtained in real time from Equations (13)-(16). As relevant

theories can be found in the relevant literature mentioned hereinabove, the same will not be explained in detail herein.

$$\Delta\mu_a(\lambda_1) = \varepsilon_{Hb}^{\lambda_1}\Delta Hb + \varepsilon_{HbO_2}^{\lambda_1}\Delta HbO_2 \text{ ---------------- (13)}$$

$$\Delta\mu_a(\lambda_2) = \varepsilon_{Hb}^{\lambda_2}\Delta Hb + \varepsilon_{HbO_2}^{\lambda_2}\Delta HbO_2 \text{ --------------- (14)}$$

$$\Delta Hb = \frac{\varepsilon_{HbO_2}^{\lambda_2}\Delta\mu_{2a}^{\lambda_1} - \varepsilon_{HbO_2}^{\lambda_1}\Delta\mu_{2a}^{\lambda_2}}{\left(\varepsilon_{Hb}^{\lambda_1}\varepsilon_{HbO_2}^{\lambda_2} - \varepsilon_{Hb}^{\lambda_2}\varepsilon_{HbO_2}^{\lambda_1}\right)} \text{ --------------- (15)}$$

$$\Delta HbO_2 = \frac{\varepsilon_{Hb}^{\lambda_2}\Delta\mu_{2a}^{\lambda_1} - \varepsilon_{Hb}^{\lambda_1}\Delta\mu_{2a}^{\lambda_2}}{\left(\varepsilon_{HbO_2}^{\lambda_1}\varepsilon_{Hb}^{\lambda_2} - \varepsilon_{HbO_2}^{\lambda_2}\varepsilon_{Hb}^{\lambda_1}\right)} \text{ ------------- (16)}$$

in which ΔHb、ΔHbO_2、$\Delta\mu_a$ are the variations of concentration of deoxyhemoglobin, oxyhemoglobin, and hemoglobin absorption coefficient , respectively. $\varepsilon_{Hb}^{\lambda_1}$、$\varepsilon_{HbO_2}^{\lambda_1}$、$\varepsilon_{Hb}^{\lambda_2}$、$\varepsilon_{HbO_2}^{\lambda_2}$ are extinction coefficients of hemoglobin to different wavelengths λ_1 and λ_2 under deoxygenated and oxygenated states, respectively, and are known parameters. The amplitude attenuation and phase delay of DPPDW in the blood can thus be obtained therefrom. Then, μ_s' and μ_a of the blood are calculated according to Equations (5)-(9). By utilizing different wavelengths λ_1 and λ_2, the absorption coefficients $\mu_a(\lambda_1)$ and $\mu_a(\lambda_2)$ of hemoglobin can be obtained with precision, and the change in hemoglobin saturation in the blood can also be measured in real time. At the

same time, an image of the hemoglobin saturation in the blood can also be obtained by using spatial scanning in combination with the solution to the diffusion equation. This invention proposes a novel polarized

5　photon pair near infrared spectroscopy, whereby measurements of the optical characteristics of a multiple scattering medium can be obtained. It is noted that results of experiments conducted·by the applicant are shown in Figures 6A and 6B, and it was found that

10　the results match the anticipated results of Equations 5 and 6 set forth herein [See Y.H. Chan et al., "The measurement of optical properties of a multiple scattering medium based on diffused photon pair density wave", Advanced Biomedical and Clinical Diagnostic

15　Systems, T. Vo-Dinh, W.S. Grundfest, D.A. Benaron, and G.E. Cohn, Proceedings of SPIE Vol. 4958,259-272 (2003)]. In summary, by scanning the test object, in combination with the solution to the diffusion equation, the image of the object in a multiple scattering medium

20　can be obtained. Moreover, by using a two-frequency laser source (preferably, two two-frequency lasers) having different center wavelengths, changes in Hb ·

HbO_2 and SaO_2, as well as the values of $\mu'_s(\lambda)$ and $\mu_a(\lambda)$

that correspond to different wavelengths, can be

25　measured with precision in real time. In case of a two-frequency, orthogonal linear polarized (or

circular polarized) photon pair, rather than a parallel polarized photon pair, propagating in the multiple scattering medium, by having a polarizer located between the scattering medium and the photomultiplier tube, a heterodyne signal can also be generated, and similar results can be achieved. While the present invention has been described in connection with what is considered the most practical and preferred embodiment, it is understood that this invention is not limited to the disclosed embodiment but is intended to cover various arrangements included within the spirit and scope of the broadest interpretation so as to encompass all such modifications and equivalent arrangements.